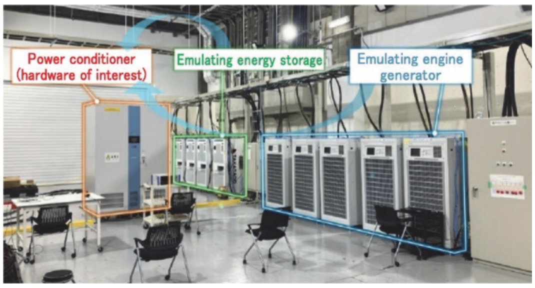
Achieving High Reliability of Power Electronics Products: Power Hardware-in-the-Loop Simulation



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For the electrification of mechanical systems and the decarbonization of power systems, the utilization of power electronics is essential. When applying advanced power semiconductor and power conversion technologies to existing systems, the verification of complex interactions, including the coupling of electrical, control, and mechanical systems, poses a challenge. Mitsubishi Heavy Industries Group has set up an environment combining actual power equipment with modeled mechanical systems to execute versatile Power Hardware-in-the-Loop Simulation for performing system verification. The test bench, using a 500 kW-class electrical equipment, enables the evaluation of phenomena up to several hundred Hz and the verification of interactions between actual equipment and models. The Group is proceeding with the application of the developed technology to a diverse range of products to improve the efficiency and reliability of system development.

1. Introduction

In modern power systems, power electronics is essential as a fundamental technology to achieve high-efficiency and high-quality conversion as well as distribution. Enhancing power system resilience is crucial due to increasingly severe disasters. This requires massive introduction of distributed power sources and corresponding power conversion technologies. In this context, Mitsubishi Heavy Industries, Ltd. (MHI) ensures a flexible and stable power supply. MHI achieves this by combining its power control technology with mechanical systems like engine generators, leveraging its strength as a machinery manufacturer.

For example, when a Power Conditioning System (PCS) is combined with an engine generator, their respective characteristics interact and affect the dynamic behavior of grid voltage and grid frequency, which are indicators of power quality. Accurately understanding and appropriately controlling these interactions leads to the improvement of the reliability of the power supply.

A specific example where interactions should be considered is Virtual Synchronous Generator (VSG) control. VSG, a representative Grid-Forming technology for grid stabilization, contributes to dynamic grid stability by implementing synchronous generator into the PCS. However, to maximize its effectiveness, comprehensive evaluation and verification are necessary, including the interactions with existing power source systems that incorporate prime movers.

As a means of evaluating the complex interactions that occur between power equipment, MHI utilizes Power Hardware-in-the-Loop (PHIL) Simulation, which is a method for performing verification by combining modeled systems with actual equipment. A key feature is the ability to conduct verification in an environment where the actual equipment is treated as if it were connected to a real system. Since 2019, MHI has been conducting collaborative research with the Center for Advanced Power Systems at Florida State University in the United States, a leader in this technology, and has mutually deepened knowledge regarding the modeling of mechanical systems and power equipment, as well as PHIL. To date, research results of this collaboration have been published through multiple academic conferences.[(1), (2)]

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This report presents a case study in which PHIL was applied to the development of EBLOX [3], a distributed power source system product that combines a gas engine, a storage battery, and renewable energy. This test was conducted at PE-Lab, an electrification system verification center established at MHI Research & Innovation Center Nagoya in 2023.

2. Power Hardware-in-the-Loop Simulation

(1) What is PHIL?

Conventionally, Hardware-in-the-Loop (HIL) has been used for system verification of controllers such as Electronic Control Units (ECUs) in the aerospace and automotive industries. **Figure 1** shows the types of HIL. The authors position PHIL Simulation as a system verification method for power equipment, distinguishing it from the conventional Controller Hardware-in-the-Loop (CHIL) Simulation used for controller verification.

In PHIL, based on the calculation results of a real-time simulator, current is injected or voltage is applied to the actual equipment via a power amplifier capable of handling actual power. Furthermore, by feeding back the behavior of the actual equipment to the real-time simulator, operations at the power boundary can be evaluated in coordination with the actual equipment.

The role of PHIL lies in its ability to evaluate dynamic behaviors in which mechanical/control systems and electrical phenomena are strongly coupled, involving actual equipment. It allows for verification in a realistic environment as to whether the electrical behavior designed in a simulation can be similarly realized in actual equipment. Moreover, PHIL is an effective means for proceeding with development together with MHI's customers. System specifications that customers may consider for future introduction can be implemented in a virtual environment, making it possible to evaluate in advance how pre-developed actual equipment will behave within the systems and environments envisioned by the customer. This enables early-stage integration with customers for specification adjustment and optimization.

In this way, PHIL plays an important role both in the context of model-based development and in terms of collaboration and co-creation with customers.

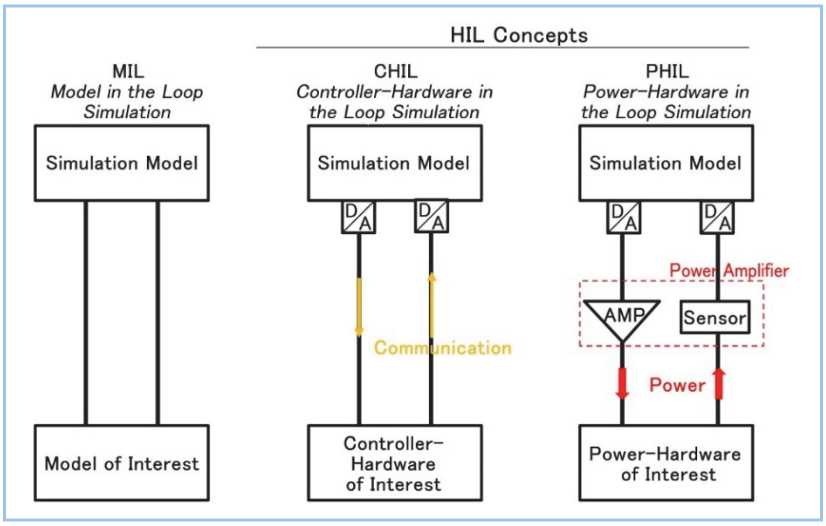

Figure 1 Types of HIL

(2) Facilities used for PHIL

Constructing a PHIL environment requires a real-time simulator and a power amplifier.

A real-time simulator is a machine that performs calculations at the same speed as actual time. MHI has accumulated extensive experience in analyzing the behavior of prime movers and mechanical systems, as well as actual machine phenomena, and possesses dynamic characteristic models based on their characteristics and limits. These models are reproduced on the real-time simulator and utilized for evaluating the operation of actual equipment.

A power amplifier is a power supply capable of wideband output. It inputs commands from the real-time simulator into the test unit, which is actual equipment, as voltage or current. It also plays the role of measuring the behavior of the test unit and feeding it back to the real-time simulator.

MHI possesses multiple real-time simulators and power amplifiers. Among them, this report presents a case study utilizing an OP4512 real-time simulator manufactured by OPAL-RT, as well as an RZ-X2-100K (DC) power amplifier manufactured by Takasago, Ltd. and an EN61800 (AC) power amplifier manufactured by Chroma.

3. The hardware of interest for verification

The verification target presented in this report is a distributed power supply system, shown in **Figure 2**. In the system, an engine generator set and a battery energy storage system supply power to a load. In this verification, the engine generator set, power load, and energy storage system are implemented in the real-time simulator, while the PCS is the actual equipment. The engine generator set includes speed governor for frequency control and an Automatic Voltage Regulator (AVR) for voltage control, and the dynamic characteristics of the generator are also represented in the model. The PCS is equipped with current-type VSG control.

In current-type VSG, when a difference occurs between the voltage angle at the PCS connection point and that calculated inside the VSG, active control is performed to increase the target power. The engine generator is responsible for forming the grid voltage, while the current-type VSG plays a role in supporting transient behaviors such as the rotational speed fluctuations and voltage fluctuations of the engine generator.

In off-grid and autonomous power supply systems, the behavior of the VSG strongly depends on the characteristics of the prime mover within its own system. Therefore, evaluation in consideration of the combined characteristics of the prime mover and the VSG is essential. Since load characteristics and system configurations vary by customer, and the target engine generator sets are also diverse, it is not realistic to verify all combinations using actual site during the development stage. However, it is unfavorable for the design process for characteristics to be clear for the first time during field tests, as this increases the risk of design changes and additional costs. Therefore, a method is required that can efficiently evaluate diverse combinations as an early stages integration.

Consequently, an approach that utilizes PHIL by using an actual hardware of the VSG-equipped PCS under development and models of the combined engine generators and other components serves as an effective approach from the perspective of front-loading.

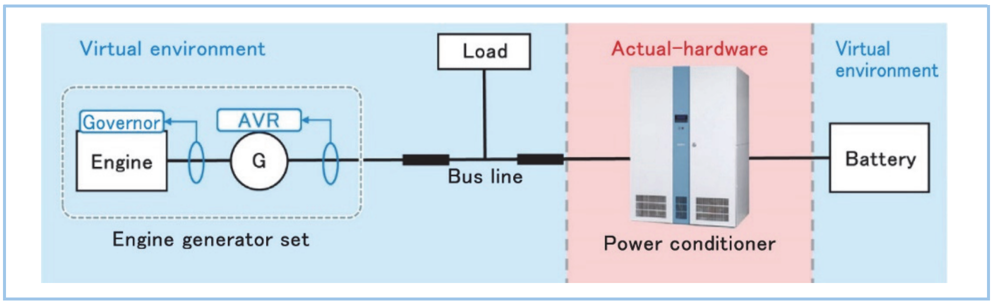

Figure 2 System of interest

4. Interface algorithm

The control logic and communication topology used to create a closed loop between the model and actual hardware is called an Interface Algorithm (IA). While various methods for IA have been proposed [(4)], the Damping Impedance Method (DIM) was deployed for the case presented in this report.

The overview of DIM is shown in **Figure 3** and **Table 1**. Note that the illustration of the DC side of the PCS is omitted. The basic operation of DIM involves using the interconnection point voltage calculated within the model as the command value for the power amplifier, and feeding back the current that flows to the power amplifier terminals to the model. The voltage measured at the power amplifier terminals is also feed-back, and its sensitivity depends on the damping impedance Z^* shown in Figure 3.

PHIL is an electrical test linked with a simulation model, and therefore, it is necessary to safely interrupt the test in the event of calculation divergence or stoppage due to abnormal behavior of the model. The detection of such abnormalities is performed based on voltage oscillations and the upper and lower limits of current. The control is established so that the closed loop is released and the power amplifier outputs a steady-state voltage when an abnormality is detected.

In system verification using PHIL, confirmation of the validity of the closed-loop environment is important. Specifically, it is necessary to evaluate up to which frequency band valid verification is possible when the actual equipment and the model form a closed loop.

The closed-loop frequency response characteristics of the PHIL environment constructed this time are shown in **Figure 4**, in which the theoretical values calculated in advance from the transfer function (Theoretical Calc.), the characteristics obtained by applying perturbation analysis to a model simulating the PHIL environment (Simulated PHIL), and the characteristics measured in the actual PHIL environment (Actual PHIL) are plotted. As shown in Figure 4, verification is possible with an accuracy of approximately 0.1% for the fundamental frequency of the power source (50 Hz/60 Hz) and of within −1 dB up to approximately 600 Hz. Furthermore, since the gain characteristics do not attenuate up to approximately 200 Hz, verification at the root mean square (RMS) level is possible, although evaluation at the instantaneous value level is limited.

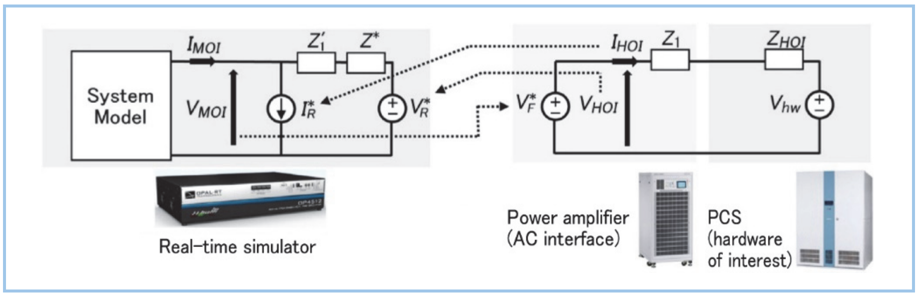

Figure 3 Interface algorithm

Table 1 Interface algorithm – Explanation of symbols

Classification	Symbol	Explanation
PCS (test unit)	V_{hw}	Voltage generated by the PCS (hardware of interest)
	Z_{HOI}	Impedance of filters, etc., attached to the hardware of interest terminals
Power amplifier	Z_1	Parasitic impedance at the power amplifier terminals
	V_F^*	Voltage generated by the power amplifier (determined by reference from the real-time simulator)
	V_{HOI}	Terminal voltage of the power amplifier
	I_{HOI}	Voltage between the power amplifier and the PCS
Real-time simulator	V_{MOI}	Voltage at the PCS connection point (used as the voltage command value for the power amplifier)
	I_{MOI}	Current flowing from the PCS connection point to the PCS
	V_R^*	Boundary voltage on the model side (feed back from the power amplifier terminal voltage)
	I_R^*	Boundary current on the model side (feed back from the power amplifier terminal current)
	Z_1'	Known as linking impedance; set so that Z_1=Z_1'
	Z^*	Known as damping impedance; set so that Z^*=Z_{HOI}

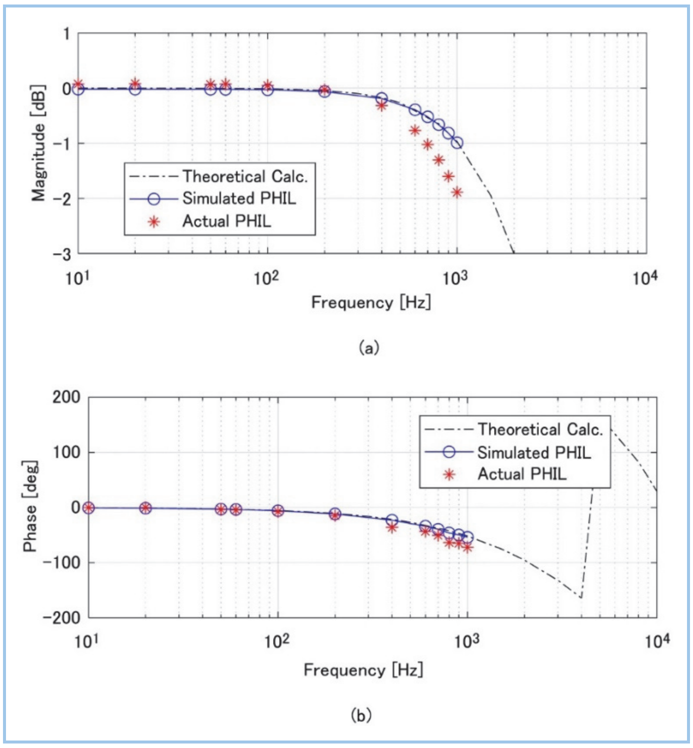

Figure 4　Accuracy evaluation of PHIL

5. PHIL testing

The current-type VSG was verified using the constructed PHIL environment. As an example, this report presents the following test cases: (1) load change and (2) control parameter adjustment.

(1)　Load change test

Figure 5 shows the results of the PHIL test, where loads were applied at levels of 10%, 20%, 30%, and 50% relative to the rating of the gas engine generator in the PHIL configuration shown in Figure 2. After the load change, the generator took on the power and the frequency decreased, and along with this frequency decrease, the PCS increased its output. This was because the phase difference between the internal voltage phase of the current-type VSG and the voltage phase of the generator widened, causing the current-type VSG to issue a command to increase the output.

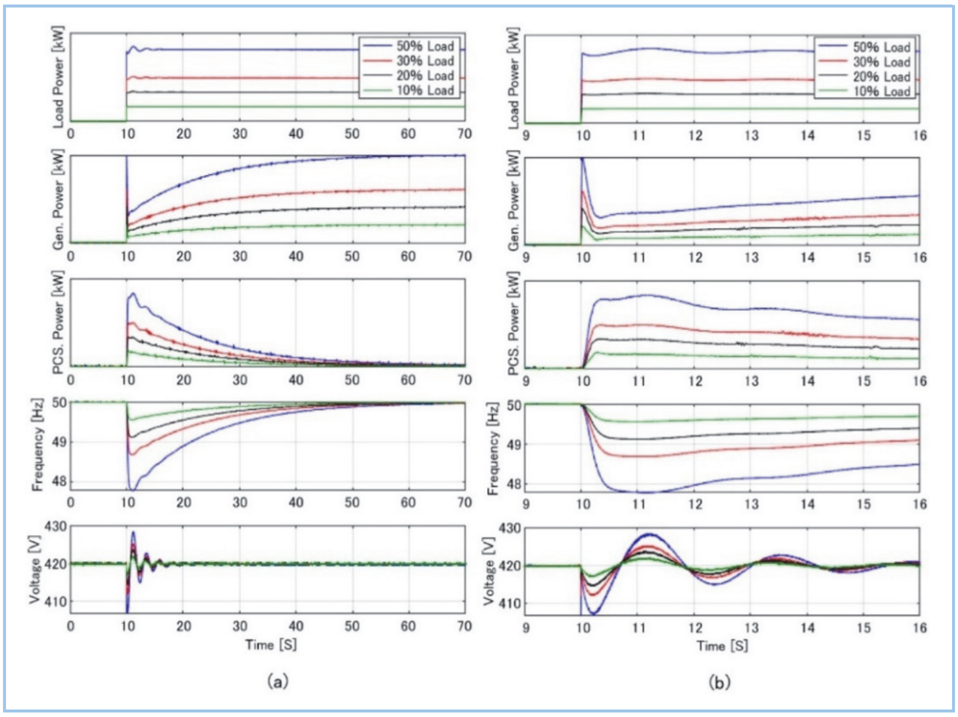

Figure 5　PHIL integration test (a: Load change test, b: Zoomed view)

(2) Control parameter adjustment

Figure 6 shows the results of a parameter study on the virtual impedance of the current-type VSG installed in the actual equipment, while observing the combined response characteristics with the gas engine generator during load change. By reducing the virtual reactance X, the PCS responds to frequency fluctuations with higher sensitivity, and as a result, the minimum frequency is improved. However, caution is required because if the PCS response is increased excessively, phenomena such as power flowing back to the gas engine generator and causing damage to the AVR diodes could occur.

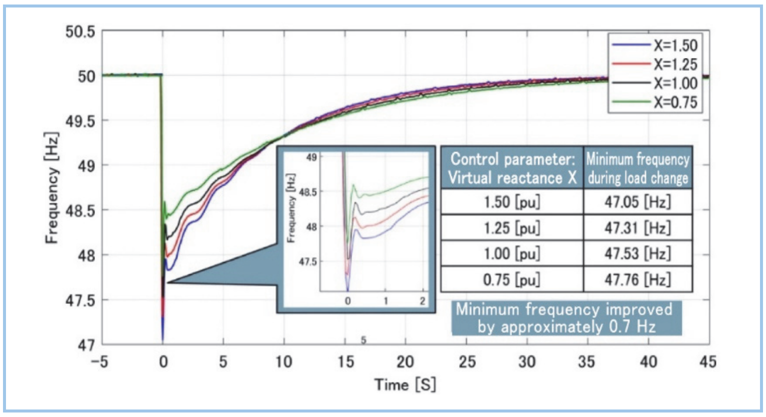

Figure 6 VSG control parameter adjustment using PHIL testing

6. Conclusion

This report presented a case study of system verification for a PCS equipped with a current-type VSG utilizing PHIL. It was demonstrated that complex interactions between actual equipment and models can be evaluated with high accuracy, confirming through load change testing and control adjustment that PHIL is an effective method contributing to the improvement of system stability. PHIL is being strengthened as a common fundamental technology applicable to a wide range of products, from civilian to defense applications, and its expansion to a diverse range of product groups is being promoted. MHI will continue to position this technology as a fundamental technology and contribute to the electrification of mechanical systems and the decarbonization of power systems.

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